CHAPTER 6

Design Considerations

6.1. Introduction and Overall Design Strategy. Once the overall remediation strategy is defined (Chapter 4), the area to be treated is defined, and subsurface extent is established, the design process can begin. What must be kept in mind is that the application of these ISTR techniques is modular in nature:

a. Thermal conduction is applied using a central vacuum well surrounded by heater wells and the pattern is repeated to cover the area to be treated. The spacing is determined by the rate of heat input versus heat losses, the target temperature, desired duration of treatment, and, to a lesser extent, by the thickness of soil to be treated.

b. ERH, whether applied in six or three phase approaches, involves a regular pattern of electrodes-hexagonal arrangements for six phase and triangular for three phase. The spacing of the electrodes is dictated in large part by the effective diameter of the individual electrodes. The diameter of the electrode array for six-phase heating is typically 5.2 to 12.2 m (17 to 40 feet), and the distance between electrodes is typically 2.6 to 6.1 m (8.5 to 20 feet) for three-phase heating. Heat losses are an input parameter for determining treatment time, but do not influence electrode spacing.

c. Steam is applied in either a 5-spot (four injection wells surrounding a central groundwater recovery well) or a 7-spot (six injection wells surrounding a central groundwater recovery well) pattern. The patterns are repeated, if necessary, to treat the area. Well spacing is determined by both vertical and horizontal hydraulic conductivity, time desired for heating, and depth and thickness of the zone to be treated. Heat losses are not typically factored into the design.

The following paragraphs discuss the factors to consider in designing remediation systems using the individual technologies. The reader is directed to ER 1110-1-8155, Specifications, ER 1110-345-700, Design Analysis, Drawings, and Specifications, and ER 1180-1-9, Design-Build Contracting, for the design requirements.

6.2. Thermal Conductive Heating. As with other thermal remediation technologies, design of a thermal conduction remediation system, whether for an in situ application (ISTD) or an ex-situ application (e.g., soil pile, in-pile thermal destruction [IPTD]), requires consideration of a number of site- and contaminant-specific factors. These include, but are not limited to, the target soil treatment temperature and desired remediation time, heater and extraction well components, energy and power delivery and distribution, vapor collection/conveyance system configuration, air quality control system, and other regulatory requirements. These design considerations are discussed in the following paragraphs.

6.2.1. *Example Calculation*. The energy balance for raising the subsurface temperature to the boiling point of water and boiling off all of the pore water initially present (e.g., to thoroughly treat SVOCs) is (TerraTherm and Weston 1997)

$$\left[\rho_R C_R \left(1 - \phi\right) + \rho_w C_w \phi S_w \right] \left(T_b - T_i\right) + \rho_w h_w \phi S_w = \frac{\beta t_b}{A} \qquad (6\text{-}1)$$

where values to electrically heat a typical silica sandy soil are:

ρ_R	=	2.650×10^{6} g•m^{-3} (density of quartz grains)
C_R	=	1.211×10^{-5} W•day•g^{-1}•°C (heat capacity of silica)
ϕ	=	0.35 (typical porosity value for sandy soil)
ρ_w	=	1.00×10^{6} g•m^{-3} (density of water)
C_w	=	4.846×10^{-5} W•day•g^{-1}•°C (heat capacity of water)
S_w	=	0.6 (typical water saturation [fraction of the pore space occupied by liquid water] as estimated from descriptions of moisture content in soil boring logs, which range from dry to moist above the water table)
T_b	=	100°C (boiling point of water at atmospheric pressure)
T_i	=	13°C (typical initial temperature value for near-surface soil)
h_w	=	0.0261 W•day•g^{-1} (latent heat of vaporization of water at atmospheric pressure)
β	=	984.2 W•m^{-1} (average power input per unit length of thermal conduction well)
t_b	=	time (days) required to heat and boil off all the initial water
A	=	(2.13 m)(2.13 m)(sin 60°) = 3.942 m^2 (area heated by each well embedded within an equilateral triangular pattern of wells spaced 2.13 m or 7 feet apart)

6.2.1.1. The first term on the left is the energy required to heat the mineral grains, the middle term is the energy required to heat the water, and the third term is the energy required to vaporize the water. The right-hand side of the equation is the energy input by a heating well into the soil volume surrounding it. Note that ϕ, S_w, T_i, β and A are typically user-specified input values, while the remaining terms are constants, except for t_b (to be solved for). This equation does not account for conductive heat losses to the adjacent formation and overlying surface, or for convective heat losses through collected gas and water that originate from outside the treated volume. Rearranging 6-1 to solve for t_b:

$$t_b = \frac{A\left\{\left[\rho_R C_R \left(1-\phi\right) + \rho_w C_w \phi S_w\right]\left(T_b - T_i\right) + \rho_w h_w \phi S_w\right\}}{\beta} \qquad (6\text{-}2)$$

For the values given above, the time t_b required to heat the soil and boil off all the water initially present is approximately 33 days. From the result of equation (6-2), it is seen that over the thermal treatment period, the amount of electrical power that each thermal well will consume, $t_b\,\beta$ = 780 kWhr•m^{-1} (238 kWhr•ft^{-1}) of heater length. Dividing by the treatment volume, $t_b\,\beta/A$ = ~200 kWhr•m^{-3} treated, which at $0.075/kWhr is about $11/cy of electrical cost.

6.2.1.2. The impact of water recharge is more complicated and requires numerical simulation to adequately address. Above the water table, there can still be recharge during remediation from rain falling directly on the site or seeping in from the subsurface around the lateral boundaries, and to a lesser extent from capillary rise if the treatment zone is within the capillary fringe zone. Below the water table, sand or gravel layers that are laterally contiguous to the targeted interval, or utility trenches, especially, offer possible pathways for subsurface recharge. The capability of thermal conduction heaters to tolerate recharge of groundwater at a given site can be estimated by comparing 1) the rate of energy injection per volume of treatment zone to 2) the energy required to heat soil grains and water within that volume to the treatment temperature. The following example calculation illustrates this.

6.2.1.3. As a first approximation, the flux of water Q_w in L•day^{-1}- that can be heated and boiled off by a row of n thermal wells, with submerged heaters b m deep may be estimated as follows (preserving the units given above):

$$Q_w = \frac{(\beta bn)}{\left[\rho_w C_w (T_b - T_i) + \rho_w h_w\right]\left(1\text{m}^3/1000\right)} \tag{6-3}$$

6.2.1.4. Thus, continuing the example, a row of 10 thermal wells, the heaters of which are initially submerged 4 m deep, has the capacity to heat and boil off approximately 1300 L•day^{-1}, or 0.24 gpm. This equation does not account for the potential of the generated steam to exert a pressure around each thermal well that diminishes or even opposes the pre-existing hydraulic gradient, and which may therefore prevent the influx of outside water into the heated zone.

6.2.1.5. Treatment of VOC-contaminated soil and waste located above the water table (i.e., in the vadose zone) by conductive heating may be considered a form of thermally enhanced soil vapor extraction (SVE). As such, the requisite data needs are addressed in large part in other guidance, such as the EM 1110-1-4001, Soil Vapor Extraction and Bioventing. With the addition of in situ heating, however, permeability becomes much less of an issue than with SVE that is not thermally enhanced. Heating soil to raise the formation temperature a modest amount may substantially increase VOC removal rates, as a 10°C temperature increase results in approximately a three to four-fold increase in vapor pressure, which in turn results in greater VOC mass transfer to the vapor phase for removal by the SVE system. Heating of low-permeability or nearly saturated soil to the boiling point of water creates in situ steam generation, whereby VOCs can be effectively steam-stripped out of the soil.

6.2.1.6. In the case of non-aqueous phase liquids (NAPL) forming azeotropes with water, steam distillation can be accomplished at a compound's eutectic point, which in the case of TCE in water is 73.1°C (versus the boiling point of TCE of 87.1ºC). Therefore, the water need not be entirely boiled off to accomplish effective treatment, in contrast to the treatment of higher-boiling SVOCs. Although steam and organic vapors are readily captured and collected in moderate–to high-permeability soil, vapor extraction in low-permeability or heterogeneous (e.g., sandy till) soil is made possible through appropriate placement and spacing of extraction wells and use of surface barriers to prevent fugitive emissions. Even in clay soil that is massive in structure, in situ steam generation opens up micro-fractures that enable steam and non-condensable, steam-stripped gases to find their way to nearby heater-vacuum wells.

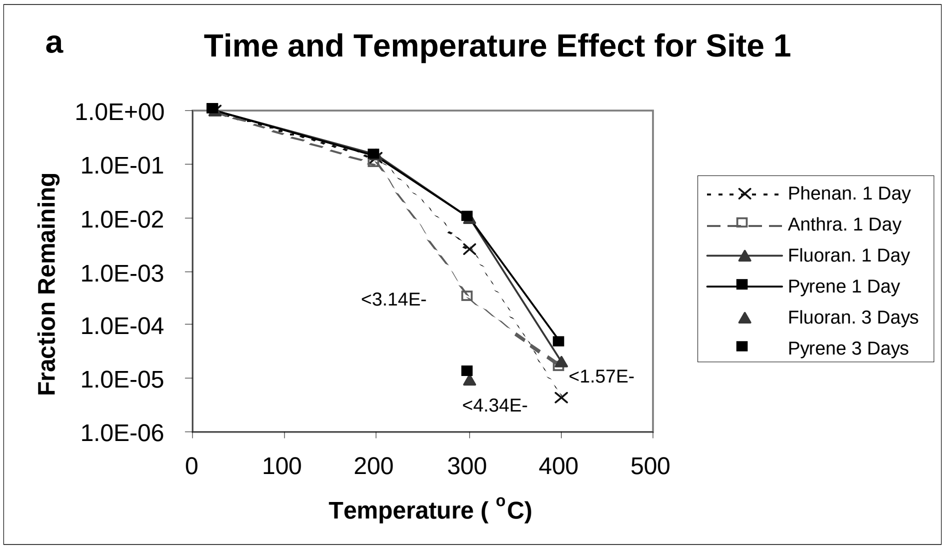
6.2.1.7. Soil with higher water content requires more energy to reach boiling than drier soil, therefore knowledge of water content is needed to estimate the heating energy budget and project duration. Laboratory treatability studies showed that a soil sample heated to a temperature of ≥ 300°C for three days was more effectively treated than a sample heated to ≥ 400°C for one day, all other things being equal (Figure 6-1). Thus, it is not necessary to achieve the boiling point of the COCs to achieve their full destruction and removal from the soil.

6.2.1.8. Achieving a temperature at which the vapor pressure of the highest–boiling COC is ≥ 10 mm Hg does, as a rule of thumb, appear to be appropriate. Reaction kinetics also govern the effectiveness of TCH and vary as a function of temperature (Baker and Kuhlman 2002). The relationship between vapor pressure of the COCs and temperature (Figure 2-3) determines whether the COC is amenable to TCH, and provides an initial indication of the temperature to which the soil must be heated to afford volatilization of the COC. Figure 2-3 shows that the full range of organic contaminants can be treated by TCH, using thermal wells operating at typical temperatures of 700–800°C. Past research and TCH field experience with high–boiling compounds such as PCBs and PAHs suggests, for example, that higher removal rates for these COCs are achieved after the coolest portions of the soil have achieve the desired temperature (Uzgiris et al. 1995, Hansen et al. 1998).

6.2.1.9. The presence of neat concentrations of highly halogenated organic liquids may require thermal wells and collection piping be manufactured of exotic metals such as Hastalloy®. These types of NAPL, upon heating, tend to hydrolyze or decompose to products such as HCl. Therefore, data regarding the nature and extent of such liquids are necessary to avoid adverse effects on materials and equipment.

6.2.2. *Subsurface Design.* Underlying any thermal conduction soil remediation design are the contaminants to be remediated and the soil matrix in which they are contained. The site-specific nature of the contaminants, their concentrations, horizontal and vertical distribution, and the soil physical properties will determine the design requirements for the other ancillary components, including component sizing, materials of construction, powerdistribution, and off-gas treatment unit processes. Careful evaluation of soil and contaminant properties is required to ensure that the design achieves the remedial goals in a safe, efficient, timely, and cost-effective manner.

6.2.2.1. *Target Treatment Temperature.* Target treatment temperature is established either through an examination of the contaminant's physical properties (e.g., melting point, boiling point, vapor pressure curves, etc.) or based on the outcome of bench or pilot testing as described in Paragraphs 5.2.1 and 5.2.2, respectively. For compounds or classes of compounds that have previously been remediated using TCH, it may not be necessary to conduct site-specific bench or pilot testing as the results and effectiveness of previous remediation projects may form the basis for selecting the desired target treatment temperature (Baker and Kuhlman 2002).



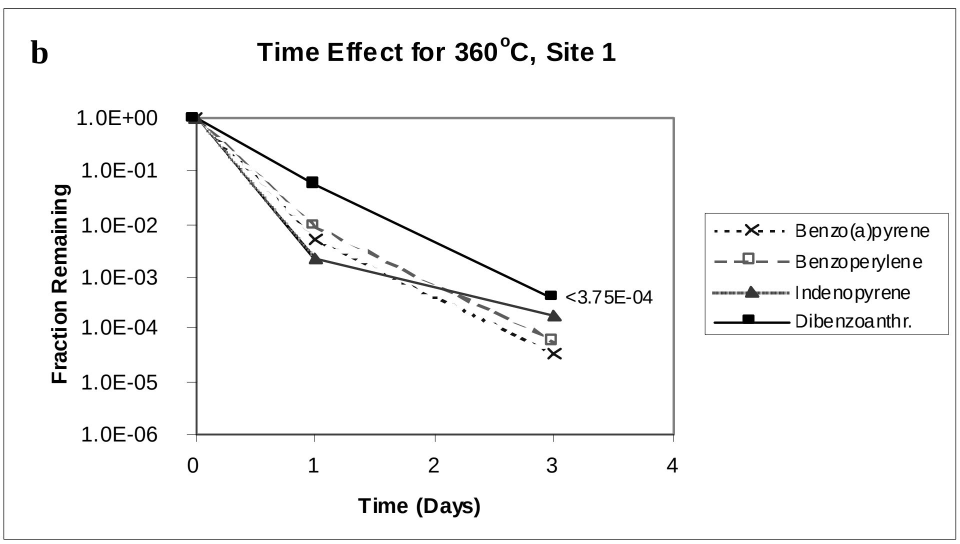


Figure 6-1. Fractions of Initial Concentrations Remaining as a Function of Time at 300°C (Hansen et al. 1998) (a) of phenanthrene, anthracene, fluoranthene, and pyrene remaining as a function of temperature; (b) of benzo(a)pyrene, benzo(g,h,i)perylene, indeno(1,2,3-cd)pyrene, and dibenzo(a,h)anthracene.

6.2.2.1.1. *Past research and field demonstrations*. (Uzgiris et al. 1995, Hansen et al. 1998, Stegemeier and Vinegar 2001) have shown that contaminants can be effectively removed from soils at temperatures considerably below their boiling points. Soil treatment should continue until the centroids of the triangles formed by the well pattern (i.e., the coolest spots) achieve and maintain the target temperature for a selected time period. In practice, it is desirable to hold the soils in the centroid locations at or above the target treatment temperature for a minimum period of 2 to 3 days to ensure complete and thorough remediation of the COCs. It should be noted however, that soils closer to the operating thermal wells will be much hotter, typically on the order of 500 to 550°C (approx. 900 to 1000°F). As contaminants are desorbed from the soil, they travel toward the heater-vacuum wells through increasingly hotter soils, over a period of hours or days. It is the extended residence time at these elevated temperatures that provides TCH with such high in situ destruction of contaminants.

6.2.2.2. *Thermal Well Spacing and Orientation*. Once the target treatment temperature has been selected, it then falls to the designer to determine the appropriate orientation and spacing of thermal wells to achieve the target temperature in an efficient and cost-effective manner. In most cases, a hexagonal heater pattern is used, with six heater wells installed around the perimeter of the hexagon and a single producer (heater-vacuum) well installed at the center of the pattern. Edge-centered heater patterns (i.e., heaters wells located at the mid-point of the perimeter segments of the hexagon) typically provide better superposition and less heat loss than apex patterns (i.e., heater wells located at the points of the hexagon, Figure 6-2).

6.2.2.2.1. This edge-centered hexagonal pattern results in a greater 3:1 heater to producer well ratio, as the heaters on the perimeter of the hexagons are each shared by two producers (refer to Figure 6-2 for an example of such a well pattern). Other patterns and ratios are possible and may be used by the designer to optimize the site design or to achieve a specific goal (e.g., early containment of contaminant vapors). For a given heater power (expressed as $W \bullet m^{-1}$), smaller spacing between the thermal wells will result in a shorter remediation period, as there is a higher energy density per unit volume of soil. Increasing the spacing between thermal wells will reduce material requirements; however, it will also extend the time required to achieve the target treatment temperature at the centroids and increase the amount of heat loss to areas above and below the target zone. Heating duration is proportional to the square of the distance between thermal wells. As such, there is a tradeoff between the cost of capital equipment (e.g., well materials, electrical distribution equipment, fume manifold piping, etc.) and operating cost, which the designer should seek to optimize. Other site-specific factors may also enter into the selection of appropriate well spacing, including minimizing disturbance to ongoing facility operations, property clean up or transfer deadlines, or seasonal weather considerations.

6.2.2.2.2. Another factor to consider in the layout of the well field may be termed "edge effects." These edge effects include heat losses along the perimeter of the treatment zone or at the top and bottom of the treatment zone, where there is no superposition of the heat fronts from adjacent wells. To counteract the edge effects around the perimeter of the target treatment zone, the thermal well field typically extends at least 1.5 m (5 feet) laterally beyond the limits of the delineated target treatment zone. To counteract the heat losses at the top and bottom surfaces of the target treatment zone, heater elements typically extend at least 0.6 m (2 feet) vertically beyond the limits of the delineated target treatment zone. In addition, at some sites, the top or bottom of the heater elements may be boosted to deliver more power to upper or lower zones.

To minimize heat losses from the top of the treatment zone, thermal insulation may need to be added in the form of a surface cover (e.g., constructed of mineral board insulation or light-weight concrete).

6.2.2.2.3. In addition, vapors and air withdrawn from the producer wells for transmission to the off-gas treatment system carry away a portion of the heat energy delivered by the producer wells, reducing their thermal efficiency by approximately 30%. Thus, it may be desirable to alter the well pattern to minimize or eliminate producer wells along the well field perimeter. In other cases, where vapor containment along a perimeter is a primary and overriding concern (e.g., adjacent to residences), it may be necessary to sacrifice thermal efficiency and have an entire segment of the well field perimeter composed of producer wells. These perimeter heater-vacuum wells can be switched over to function as heater-only wells once vapor capture at the edge of the contaminated zone has been achieved.

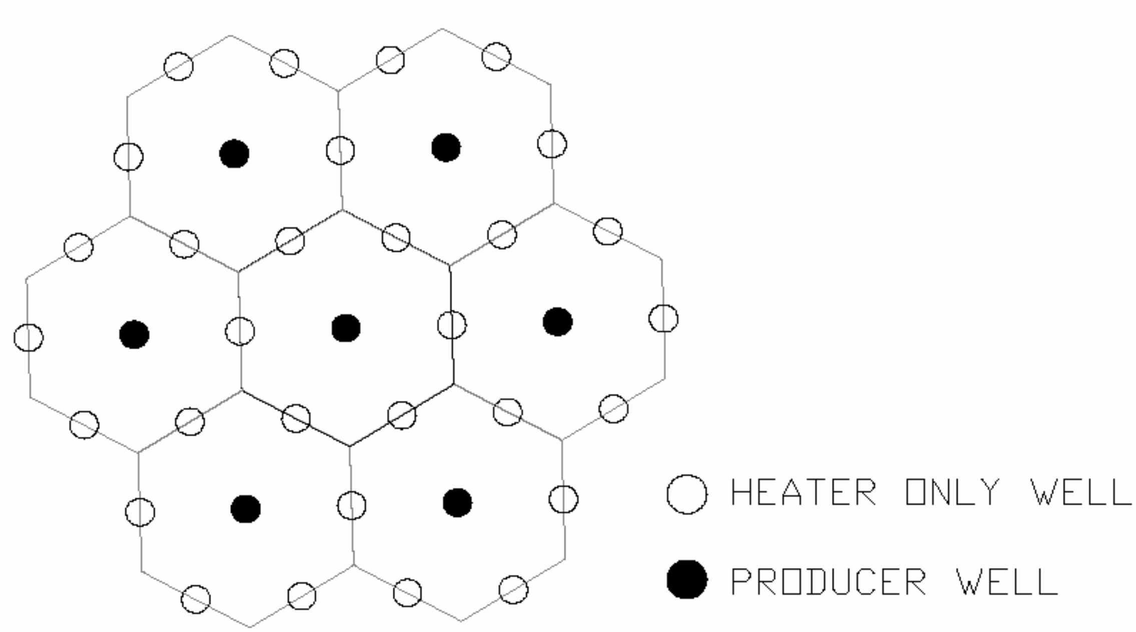


Figure 6-2. Example of 3:1 Edge-Centered Pattern (producer well = heater vacuum well).

6.2.3. *Thermal Wells*. As stated previously, there are two types of wells used for thermal conductive heating projects: heater-only wells and heater-vacuum (producer) wells. These are discussed in the following paragraphs.

6.2.3.1. *Heater-Only Wells*. Heater-only wells consist simply of a heater element suspended in a protective can (Figure 6-3). The can, in most cases, is simply a segment or segments of pipe, sealed at the bottom. The heater element must be suspended in such a way that the heater can is electrically isolated from the heater element (when electrically powered heater elements are used). Typically, a drive point is affixed to the bottom of the can. Selection of heater can diameter, schedule (wall thickness), and materials of construction will depend upon the well configuration, installation method and depth, the contaminants of concern, and the expected operating temperature of the heater elements. Typically, heater cans are constructed of stainless steel owing to its significantly better corrosion resistance at elevated temperatures than carbon steel. For sites with particularly heavy corrosive contaminant loading, it may be necessary to upgrade to a higher-grade corrosion resistant alloy (e.g., Hastelloy C-276, C-22, Inconel 600, etc.) In most cases, heater cans used by TerraTherm are 7.6 cm (3-inch) schedule 40 stainless steel, although various diameters, wall thicknesses and materials have been used. In some cases, it is possible to install the heater elements directly into the soil without a can; however, this makes servicing and replacement of heater elements during operation more difficult and costly, and is therefore, typically avoided.

6.2.3.2. *Heater-Vacuum Wells*. Heater-vacuum wells, or producers, consist of a flat-bottomed heater can as described in the previous section, suspended in a well screen (Figure 6-4). Well screen slot size, screen placement, and sand pack selection may follow typical SVE system design methods (refer to EM 1110-1-4001). Screened sections may be continuous over the entire heated interval or focused in specific segments of the heated sections where the greatest load of contaminant laden vapors is expected to be produced. Selection of screen can diameter, schedule (wall thickness), and materials of construction will depend upon the factors described in the preceding paragraph. Typically, the selected well screen is at least one or two nominal pipe sizes up from the heater can suspended within it. In most cases it is strongly recommended that a seal be installed in the annular space between the borehole wall and the heater-vacuum well casing to prevent leakage of vapors and steam upward thorough the borehole. Typically, a lean concrete or concrete grout seal is preferred over a hydrated bentonite seal as it will withstand the heat and resist desiccation longer than bentonite alone.

6.2.3.3. *Thermal Well Installation Methods*. Thermal wells may be installed using conventional hollow stem auger drilling equipment. However, because it is desirable to maintain close soil to well contact for efficient thermal conductive heating whenever possible, it is desirable to directly drive the heater-only wells into the soil, thereby locally increasing the density and effective thermal conductivity (i.e., there is more grain to grain contact) of the soils around the heater can. Given the relatively large diameter and closed bottom of the heater cans and the large number of thermal wells typically installed at a site, the rig selected for driving thermal well cans must have a sufficiently high hammer cycle rate and have sufficient down force to drive the cans efficiently.

6.2.3.3.1. Heater-vacuum wells are typically installed in augered holes, as driving screens can damage the screen and can lead to soil smearing and clogging of the slots. Solid stem augers may be used if soil conditions are such that the boreholes will not collapse when the auger is withdrawn to allow installation of the screen. This method offers the advantage of faster installation and minimizes drill cuttings; however, it is not possible at all sites. Otherwise, hollow stem augers are typically used.

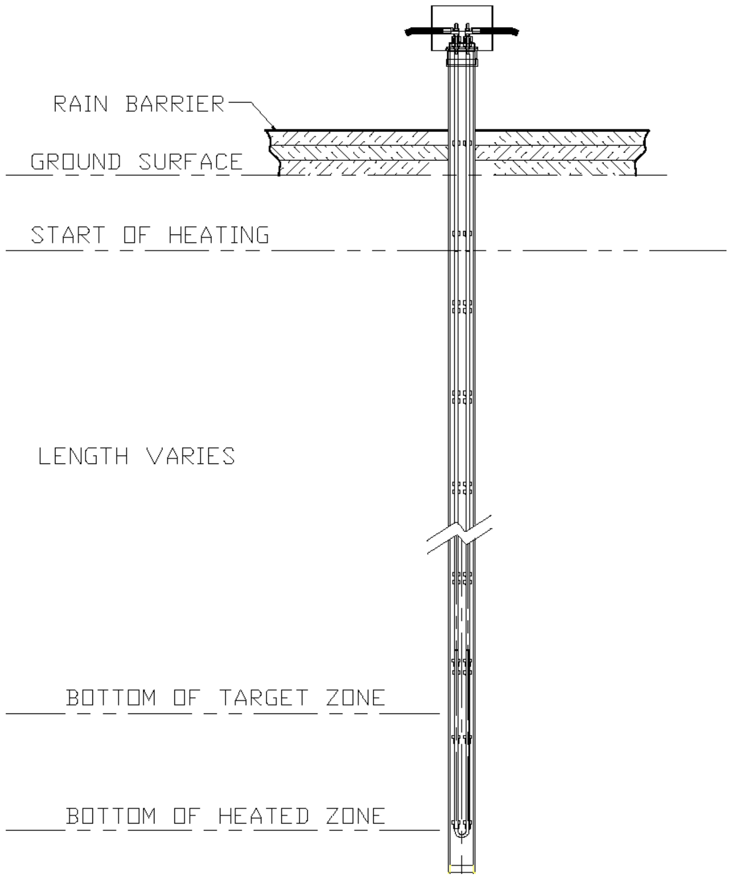


Figure 6-3. Typical Heater-Only Well.

6.2.3.3.2. Rotary sonic installation methods also work well and achieve the goal of maintaining close contact between vibration driven cans and the surrounding soil. Heater-vacuum well screens installed by rotary sonic drilling are typically installed in a casing that has been vibrated into the ground. The casing is then withdrawn as the sandpack is installed. Rotary sonic methods can achieve good installation production rates (installed meters per day). This technique works well for sites with a significant amount of debris; however, this method is substantially more expensive than hollow stem auger installation methods.

6.2.3.3.3. Heater-vacuum well screens and heater cans may also be installed using angled, horizontal, or directional drilling methods. In this case, minor modifications are necessary to ensure that heater elements and producer well cans are centralized. Material selection may also need to consider the bend radius of the proposed angled or directionally drilled borehole. Installation in trenches is an additional option.

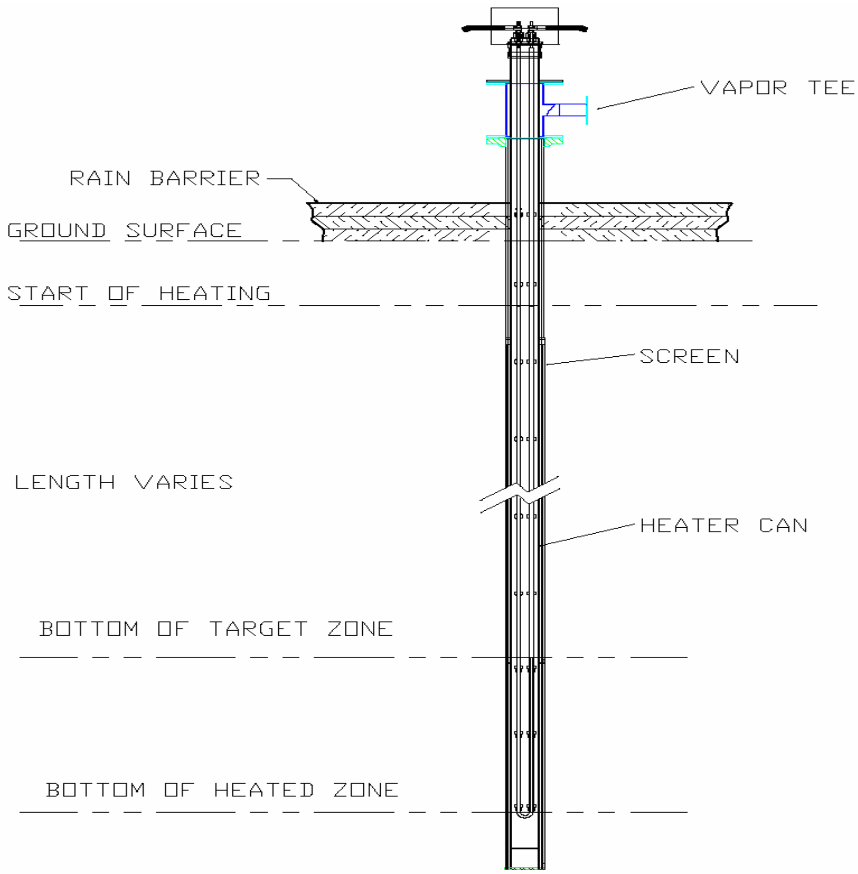


Figure 6-4. Typical Producer Well.

6.2.3.4. *Quality Control Requirements*. Well and screen materials need to be inspected to ensure that the components are of the desired quality and material composition. In vertical applications, a maximum tolerance for deviation from verticality, particularly in long or deep wells, to ensure that the concentric components (e.g., heaters in cans, and cans in heater-vacuum wells) can be installed after the wells are drilled or driven is necessary.

6.2.3.5. *Groundwater Control Systems*. At sites where groundwater intersects the target treatment zone or where water-bearing stringers may transmit groundwater to the treatment zone, groundwater control may be required. It may not be possible for the thermal wells to deliver sufficient energy to boil off infiltrating groundwater (or surface water runoff, for that matter) and still raise the temperature of the target soils above the boiling point of water. Excessive or uncontrolled groundwater or surface water infiltration may limit the ability of ISTD to achieve the required target treatment temperature in some or all locations throughout the target treatment zone. Therefore, it is critically important to identify potential sources of groundwater or surface water infiltration and take appropriate measures to control them. In the case of groundwater, these control measures may include sheet pile or jet-grout barrier walls keyed into an aquitard layer, well-point dewatering systems, trenched or horizontally or directionally drilled dewatering wells, or freeze wall barriers. These actions may have a significant cost impact on the project. It may be cost-effective to remove any recoverable groundwater prior to the start of heating at those sites where groundwater can be readily contained and pumped out of the target treatment zone.

6.2.4. *Energy Input and Conveyance Systems*.

6.2.4.1. *Energy Requirements*. Assuming negligible water infiltration or recharge into the target treatment zone and neglecting edge losses, a fixed amount of energy is required to raise the temperature of the soil to the boiling point of water, boil off a single pore volume of soil moisture and then, for most TCH sites, raise the dried soil to the superheated target treatment temperature. For sites with relatively low boiling contaminants (e.g., PCE, TCE, benzene, styrene, etc.), it is not necessary to boil off the soil moisture, provided there is sufficient permeability in clayey soils to remove contaminants without drying the soil. At these sites it may be sufficient to simply approach the boiling point of water (100°C, 212°F) to achieve the desired degree of contaminant removal or destruction. Therefore, the energy required to raise the soil to the desired temperature can be estimated relatively easily using an analytical spreadsheet calculation. Numerical modeling may be used to provide a more accurate estimate of the energy requirements, allowing for the benefits of superposition, convection, edge losses, heat loss through producer wells, infiltration, and other factors. As a general rule of thumb, most soils cannot accept more than approximately 985 $W \cdot m^{-1}$ (300 $W \cdot ft^{-1}$) of heat input from a line source (such as a thermal well) (Stefemeier and Vinegar 2001). During the early stage of heating, when the soil is cool and moist, its thermal conductivity is high and the soil is capable of absorbing high heat input from the heater with only a moderate increase in temperature. As the soil is heated and dried, the thermal conductivity decreases, thereby accelerating the natural temperature rise. Eventually, a stabilized heating rate is attained with relatively small increases in temperature at the well.

6.2.4.2. *Heat Delivery Mechanisms*. Energy in the form of heat may be delivered to the soil using a number of methods, including: electrical, gas combustion, or other methods. Electrically powered heater elements, proprietary stainless steel elements, and mineral insulated cable elements have been used in all testing, demonstration, and full-scale projects to date. Gas combustion soil heaters, which are claimed and protected by early ISTD patents, are currently under development for specific applications.

6.2.4.3. *Heater Elements (Electrical)*. Electrically powered heater elements may be operated with or without the use of controllers. In the first case, a power controller, typically a silicon-controlled rectifier (SCR), is used to modulate (automatically or manually) the power delivered to the heater elements based on the temperature input from one or more thermocouples on or in the immediate vicinity of the heater element. In the controllerless configuration, the resistive properties of the metal heater element (increasing resistance with temperature) may be used to construct essentially self-regulating heaters. In this configuration a constant voltage is applied to the heaters. As the heater element gets hotter, its resistance increases and by Ohm's Law, the current decreases, resulting in a "self-regulating" watt output. The preferred approach is to use self-regulating heaters; however, for specific applications, controlled-output heaters may be desirable (e.g., for ramping up to temperature slowly, or in instances where it is desirable to maintain the heaters or soil below a certain temperature).

6.2.4.3.1. Careful consideration of the thermal expansion of the heater element, the heater can, and for heater-vacuum wells, the well screen, is required. Heater-only cans and heater-vacuum well screens are constrained at the bottom by the soil matrix and therefore tend to expand upward when heated. However, the heater elements suspended in the cans and heater cans suspended in heater-vacuum wells are free hanging and tend to expand downward when they are heated. Adequate room for thermal expansion is required to prevent damage to the components. This is critically important on electrically powered systems, where contact between components during heating could potentially cause damage or, although unlikely, could cause the heater to ground out on the can.

6.2.4.4. *Wellhead Power and Vapor Connections*. Wellhead power connections are made in weatherproof electrical junction boxes that are attached to the heater cans with an electrical conduit compression fitting. Cold pin conductors welded to the free ends of the heater rods extend through an electrically insulated bulkhead or support plate at the top of each heater can, and into the junction box. Mechanical lugs or other suitable terminations are used to attach the power cables to the heater rods.

6.2.4.4.1. Heater-vacuum wells are typically completed with a flanged vapor tee, through which the internal heater can is inserted. The lower flange of the vapor tee mates with the well screen riser and the upper flange on the vapor tee mates with a plate flange welded on the internal heater can, thus sealing the well screen annulus. Vapors exit through the branch of the tee to the piping manifold, under vacuum. The branch of the tee may also be fitted with an individual flow control valve, sample port or pressure monitoring port where desired. The internal heater can riser extends above the vapor tee, such that electrical connections for heater-vacuum wells are similar to those for heater-only wells.

6.2.4.5. *Vapor Conveyance Piping Systems*.

6.2.4.5.1. Design of TCH vapor conveyance piping should follow existing USACE piping system design guidance. In selecting and specifying piping system components (including pipe, fittings, and valves), designers must consider the changing composition and state of the vapor stream (from relatively cool, moist steam to hot, dry air). Piping system materials of construction must be sufficient to withstand the nature of the contaminants, the potential acidity of the vapor stream, and the elevated temperatures to which they will be exposed. Corrosion is often most troublesome in parts of the system where liquid can collect. Design of the system should provide against zones of liquid accumulation. Allowance must be made for thermal expansion as the piping system is heated to operating temperature.

6.2.4.5.2. Typically, supplemental heat must be added to the piping system to prevent the extracted vapor stream from condensing in the conveyance piping. Supplemental heat may be added either through internal insertion heaters (installed in cans inside the manifold pipe spools) or through external heat tracing, as appropriate to the particular case. Insulation must be provided for personnel protection and to minimize heat losses. In some cases it is desirable to allow vapors to condense in the pipe manifold and withdraw the condensed liquid for treatment separate from the air stream. In this condensing case, insulation need only provide protection for personnel exposures. Because the piping systems are typically installed outdoors, external jacketing must be weatherproof.

6.2.4.5.3. Manifold piping spool pieces are typically pre-fabricated in standard lengths and fitted with flanged ends to allow a relatively rapid assembly of the manifold in the field. Since the TCH piping system is typically a temporary installation (on the order of months), the piping network is frequently supported on portable jack stands. However, in areas prone to seismic activity or where the piping system will be in place for an extended period, more elaborate supports and bracing may be required.

6.2.5. *Aboveground Systems*.

6.2.5.1. *Power Distribution*. In electrically powered TCH systems, there can be a very significant power demand, depending upon the volume of contaminant to be remediated. Once a preliminary estimate of the power requirement is available, designers should consult with the on-site engineers, infrastructure managers and local utility company representatives to determine whether there is sufficient power transmission and distribution capacity at the facility or off the local grid. Designers should weigh the cost and schedule impacts of running new power transmission lines from a nearby substation versus operating the TCH project in multiple smaller phases to reduce the overall demand load of a large project.

6.2.5.1.1. Power is fed from the high-voltage transmission lines to a transformer with a typical secondary voltage of 480 VAC. Power is fed from the transformer to a fused main disconnect switch or a main circuit breaker in an electrical switchboard. There may be one or more switchboards to distribute power to the well heaters, manifold pipe heaters, and vapor treatment equipment. Vapor treatment equipment may be operated from a packaged motor control center (MCC) or fed separately through individual motor starters, or variable frequency drives (VFDs). Well heaters can be designed to operate at a variety of voltages to balance circuits and obtain the desired power output; therefore, power distribution depends on the site configuration. Owing to the temporary nature of TCH installations and to speed field construction, portable power cables (also called mining cables) are typically used to feed power from the circuit breakers to the well field heaters.

6.2.5.1.2. Where required by National Electrical Code (NEC, NFPA 70) and local codes, distribution gear must be provided with ground fault protection. Electrical distribution gear should be provided with appropriately sized over-current protection. Designers must remember to consider the length of heater power cable runs as well as the fact that the heaters will operate continuously once energized, and apply appropriate component size adjustments to comply with NEC requirements for continuous duty loads and minimizing voltage drops.

6.2.5.1.3. Conductive components within the well field should be bonded and grounded. In addition, transformers, distribution panels, process equipment, trailers, and other conductive system components should be bonded and grounded in accordance with the National Electrical Code and any local requirements.

6.2.5.2. *Vapor Treatment Systems*. Vapor treatment systems for field pilot tests were discussed in Paragraph 5.2.2 and a typical system is depicted schematically in Figure 5-4. Vapor treatment systems for full-scale systems are similar to pilot-scale systems, although typically larger to accept the larger flow rates in full-scale systems. Vapor treatment systems may be as simple as one or more carbon adsorbers or may require a more comprehensive vapor treatment system consisting of a thermal oxidizer, heat exchanger, acid gas scrubbers, silt knock outs, and one or more carbon adsorbers. Selection and sizing of vapor treatment system components will depend on the expected peak vapor generation rate (typically estimated at a peak of 0.028 standard cubic meters per minute (1 scfm) of vapor per kW of heater power), the projected COC loading, and the applicable air emission limits.

6.2.5.3. *Emission Monitoring*. Emission monitoring requirements will vary depending on the site COCs and the applicable air emission standards. Emission monitoring can be as simple as daily screening of exhaust vapors with a flame ionization detector (FID) or photo ionization detector (PID), or may entail the use of a continuous emission monitoring (CEM) system. Typically, the former is used with a simple carbon-only vapor treatment system while the latter is usually required for vapor treatment systems that incorporate a thermal oxidizer. Typical CEM system monitoring parameters for ISTD applications include Wet O_2, Dry O_2, CO, CO_2, and total hydrocarbons. Dust and opacity monitoring, and chlorine/HCl monitoring may also be required. In some cases, stack testing using isokinetic sampling methods may be required to comply with emission standards.

6.2.5.4. *Emergency Power Supply*. A source of standby power, typically a diesel-powered emergency generator, is required to enable continuous operation of vapor collection and treatment equipment in the event of a temporary interruption in shore (grid) power, as the hot soil mass will continue generating steam and vapors during a power interruption. The emergency power supply may also be used to feed power to the fume pipe manifold to ensure that the pipe heating system remains operational. An automatic transfer switch is the preferred method of starting the generator in the event of a power interruption, although for a continuously manned site, a manual transfer switch may be acceptable.

6.2.5.5. *Design Review Checklist*. The Design Review Checklist in Appendix C provides a general guideline for information required to carry a design for an ISTD project from conceptual level through completion.

6.3. <u>Electrical Resistivity Heating</u>.

6.3.1. *Subsurface Design*. The most cost-effective electrode spacing for an ERH system depends on a complex interplay among various factors. However, in most cases, an electrode spacing of between 2.6 and 6.1 m (8.5 and 20 feet) is selected. Some of the factors that influence electrode spacing within this range include:

a. Electrode borehole diameter—larger electrode boreholes provide a greater surface area for electrical current flow into the soil and, thus, can be spaced further apart.

b. ERH power density—high-applied power requires greater electrode surface area, either larger electrodes or more (tighter spaced) electrodes. Application of high power allows faster remediation.

c. ERH energy (power × time) density—high-applied energy (needed for high boiling point compounds [>100 and <150ºC], very high percentage reductions, or because of high TOC) requires a tighter electrode spacing to ensure that the energy is applied in the most uniform possible manner.

d. Treatment of deep soils increases the drilling cost; therefore, greater electrode spacing is more cost-effective.

e. The type of soil, the state of water saturation, and the electrical conductivity of the soil have almost no impact on the most cost-effective electrode spacing.

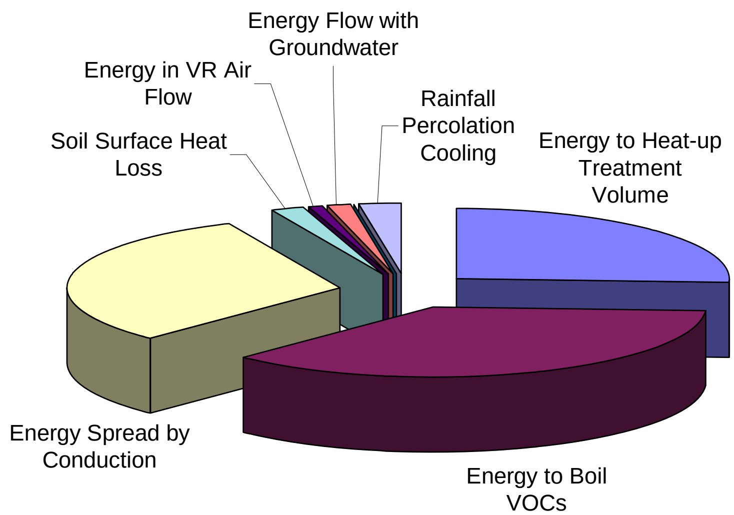


Figure 6-5. Typical ERH Energy Distribution in Subsurface.

6.3.1.1. Electrodes are usually installed by hollow stem auger or some other conventional drilling technique and can be installed in angled boreholes. Current is carried down the borehole by either a steel pipe or a Teflon®-insulated electrical cable that is connected to a metal electrode element. The region surrounding the pipe or electrode element is backfilled with granular graphite or steel shot (or a combination thereof), which conducts the electricity to the soil surrounding the borehole. Care should be exercised to ensure that the steel shot does not displace bentonite seals during construction. These backfill materials have a particle size similar to coarse sand and can be used as a well sand pack.

6.3.1.2. To maintain soil moisture and electrical contact, a ¼-inch Teflon tube is often inserted into the electrode backfill to provide a method to drip potable water. If the electrode is completed in geological material that readily transmits water, then a drip system is usually not required. Electrodes can also have multiple completions, and up to six independent electrode elements have been installed in a single borehole to allow independent heating of six different depth zones.

6.3.1.3. Electrodes can also be installed by driving a steel pipe into the ground. This method of electrode installation is usually reserved for treatment of shallow soils under saturated water conditions.

6.3.1.4. Electrode boreholes often include one or more co-located vapor recovery wells. These vapor recovery wells may consist of steam vents that are located below the water table and operated at negative pressures for vapor capture. Within the vadose zone, there are trade-offs associated with co-locating a vapor recovery well within the electrically conductive zone of an electrode: the vapor recovery well tends to desiccate the soils immediately adjacent to the borehole, resulting in restricted electrical conduction.

6.3.1.5. The purpose of the vapor recovery wells is to collect the produced vapors and prevent vapor migration. It is not necessary to try to drive airflow through the lithological unit (as in an SVE system), because it is the uniform in situ steam generation of ERH that produces the steam carrier gas for removal of VOCs from the soils as vapor. A surface seal is incorporated into the installation to maintain negative pressure to collect the vapors and to prevent steam breakthrough or exposure at the surface.

6.3.1.6. If the depth to water is quite shallow (less than 5 feet [1.5 m] below grade), then horizontal vapor recovery wells or trenches may be preferred. Further, if there is the potential for a shallow water table to rise above the ground surface during the treatment process as a result of climatic conditions or generation of steam, controls may be necessary to prevent electrical hazards or exposure to hot liquids and vapors.

6.3.2. *Energy Input and Conveyance Systems*. The vapor recovery piping is usually constructed of chlorinated polyvinyl chloride (CPVC), a high temperature version of PVC. This piping has the advantage of relatively low cost and good chemical and corrosion resistance. Its low heat conductivity keeps the outer surface sufficiently cool to avoid a burn hazard and no insulation is required.

6.3.2.1. CPVC expands significantly when heated. This requires some care in piping design, as the vapor recovery piping will expand by about 0.4% in length. The wells are especially rigid locations and the use of piping offsets or expansion loops within the well field is often required. Below grade piping installations often require expansion joints. CPVC piping will lose strength and sag as temperatures rise. This must be considered in the design of piping supports.

6.3.2.2. Although CPVC has been successfully used in thousands of vapor recovery wells and for miles of recovery piping at thermal remediation sites, it is not recommended for use in monitoring wells that are screened completely below the water table. The headspace of such a well does not have free exchange with the vadose zone. During steaming operation, steam and VOC vapors will collect in the headspace of a submerged screen well. The top of the well will be a condensation zone and separate phase VOCs are likely to condense there. The combination of high VOC exposure, high temperature, and slight pressure has caused submerged screen CPVC monitoring wells to fail and vent steam to the atmosphere. For this reason, stainless steel is recommended for submerged screen monitoring wells. In an ERH application, care must be take to ensure that the metal well does not transmit below grade voltage to create a surface voltage hazard.

6.3.3. *Above-Ground Equipment*. The vapor recovered from the wells usually consists of about 75% steam, 25% air, and a small fraction of a percent of the target contaminant. The CPVC vapor recovery piping is connected to a steam condenser that includes a vapor liquid separator. A silt knock-out should also be considered in the design. The steam condenser cools the air and VOC vapors to near ambient temperatures for conventional vapor treatment. The target VOCs do not condense in the condenser; in fact, a condenser is an ideal application of Henry's Law and over 99% of common VOCs remain in the vapor state as they pass through the condenser. After cooling by the condenser, conventional vacuum blowers and vapor treatment methods can be used. The vapor treatment process is similar to SVE systems, except that the typical flow rates are lower (because about 75% of the flow has been condensed and removed) and the vapor concentrations are much higher. These effects reduce the overall vapor treatment costs considerably in comparison to conventional SVE systems.

6.3.3.1. Two types of steam condensers are common: air-cooled and water-cooled. Air-cooled condensers are simpler and less expensive. However, they can only cool the extracted vapor to a temperature about 20°F above ambient. This leaves about twice as much absolute humidity in the air as a water-cooled condenser and, thus, reduces GAC loading efficiency. A water-cooled condenser uses a recirculated water stream and heat is rejected to the atmosphere via a cooling tower that evaporates a portion of the recirculated water. A water-cooled condenser can cool the extracted vapor to ambient temperatures; in low humidity environments, the vapor is cooled a few degrees below ambient temperatures. A water-cooled condenser requires a source of make-up water to replace the water that is evaporated in the cooling tower. Typically, the condensed steam is recycled for use as this make-up water. This results in the emission to the atmosphere of a fraction of 1% of the extracted VOCs (as described above); however, recycling of the steam condensate eliminates the need for an independent condensate water treatment system and may eliminate the need for water discharge.

6.3.3.2. An ERH Power Control Unit (PCU) adjusts the utility voltage to the proper level to deliver to the electrodes. The electrode voltage inversely varies with soil electrical conductivity. Soil electrical conductivity usually parallels groundwater total dissolved solids (TDS) concentrations. The PCU also includes safety interlocks to shut down the ERH system in the event of an unsafe condition and includes a temperature monitoring system. The PCU should include a modem connection to allow remote monitoring and control of all aspects of the heating process. The vapor recovery process can also be automated and remotely monitored; however, this is generally not cost-effective for simple vapor treatment systems such as GAC.

6.3.3.3. Where required by National Electrical Code (NEC, NFPA 70) and local codes, distribution gear must be provided with ground fault protection. Electrical distribution gear should be provided with appropriately sized over-current protection. Designers must remember to consider the length of heater power cable runs as well as the fact that the heaters will operate continuously once energized, and apply appropriate component size adjustments to comply with NEC requirements for continuous duty loads and minimizing voltage drops.

6.3.3.4. Conductive components within the well field should be bonded and grounded. In addition, transformers, distribution panels, process equipment, trailers, and other conductive system components should be bonded and grounded in accordance with the National Electrical Code and any local requirements.

6.3.4. *Design Review Checklist*. The following ERH design issues should be reviewed:

a. Has the ERH system designer taken measures to protect workers and the general public from the hazardous voltage that will be applied in the subsurface? Appropriate measures include:

(1) Physical separation - usually at least 20 feet separation from electrically conductive components is required for worker safety and at least 30 feet for general public safety.

(2) Electrical insulators - these can include plastic or rubber materials or can include rounded pea gravel to cover large areas.

(3) Electrically conducting material to create an equipotential surface-an example would be a metal grid over the site to damp the surface voltage to a low value. Monitoring wells should be locked shut such that a “danger tag-out” is required to open the well.

b. Has the ERH system designer taken measures to protect workers from steam and high temperatures?

(1) Monitoring wells provide the greatest risk; if the top of the monitoring well screen is below the water table, the monitoring well will pressurize during ERH operation.

(2) If a monitoring well is opened under pressure, this can lead to a geyser effect.

c. Has the ERH system designer considered the effects of elevated subsurface temperatures on underground utilities?

(1) If the top of the heated interval begins 5 feet or more below grade, then utilities at common burial depths are generally not a concern.

(2) If utilities are located within the heated volume, the greatest concern relates to plastic piping and electrical power conductors (which also have internal ohmic heating from the current they carry).

(3) Metal utilities, fiber optics, and concrete or clay sewer lines are not very temperature-sensitive.

(4) Utility trenches may have the ability carry vapors and steam away from the treatment area, which would not only result in a loss of control during treatment, but may represent a health and safety risk is the steam or vapors are carried offsite.

d. Has the designer considered potential for migration of vapors into basements?

e. Has the designer considered a rising shallow water table to the ground surface from climatic events or steam generation and the potential for electrical hazards or exposure to hot liquids and vapors?

f. Are the soils expansive clays and will soil dessication and the resultant shrinkage that would occur in the vicinity of the water table a concern for foundations and utilities?

g. How will vapor and steam be captured? Within the vadose zone, the application of vacuum influence will capture the steam and vapor. Within the saturated zone, low permeability lenses can pool or divert rising steam and VOC vapors.

6.4. Steam Enhanced Extraction.

6.4.1. *Subsurface Design*. The design of a full-scale steam injection system should maximize the removal of contaminants from the subsurface in an efficient manner. To achieve this objective, the design should incorporate thermal modeling, analysis of site hydrogeological and contaminant distribution data, and analysis of mass movements both above and below the source zone.

6.4.1.1. To control the migration of the contaminants, steam should be injected outside, below, and above the source zone.[*] The injected steam creates a thermodynamic driving force, moving the contaminants towards the center of the target volume, where liquids and vapors will be extracted. The success of this strategy depends on the careful delineation of NAPL in the source zone. The vertical and horizontal extent of the NAPL should be well defined, as discussed in Chapter 3. In this way, steam will always sweep from the outside in, carrying NAPL with it and thus preventing NAPL spreading to the surrounding area. Downward NAPL migration can be prevented by sweeping steam below the source zone first (Heron et al. 1998b, Gerdes et al. 1998). This creates a steam blanket below the NAPL. Droplets sinking into this zone will be vaporized and carried with the steam to the extraction well. Research conducted in Germany has also shown a benefit in the co-injection of air with the steam in preventing downward migration of NAPL (Betz et al. 1998, Schmidt et al. 1998). The co-injection of air should be examined through additional design modeling work to determine its feasibility at the site.

* This assumes a single array of steam injection wells surrounding a vapor and groundwater recovery well. For applications having multiple arrays of wells, recovery would occur in the middle of each array.

6.4.1.2. As steam is injected into the subsurface, it will propagate outward and upward from the injection well screen, in a shape determined by the horizontal and vertical permeabilities of the soil, and by the steam injection rate. The lateral radius of the steam zone surrounding each well depends on the soil characteristics (the greater horizontal to vertical permeability typical of sedimentary deposits helps to spread steam laterally around the well). For steam injected into the vadose zone, good horizontal sweep is expected, as the steam flow is only mildly affected by gravity forces. Enough steam injectors should be used to ensure that a very uniform steam zone develops below the NAPL zone.

6.4.1.3. If multi-level wells are used, steam is typically injected into the NAPL zone only after the upper and lower zones reach steam temperature. Cyclic steam injection may start when the entire zone reaches steam temperature, either by varying pressure in a given well, or by varying the wells where steam is injected. At the same time, the vapor extraction system should be operated continuously. This will create large pressure changes in the target volume through time, which has been shown to enhance the removal of contaminants from low permeability zones (Itamura and Udell 1995). The cycling is expected to: 1) create a condition where the pressure in the soil pores is less than atmospheric, resulting in “flashing” of residual NAPL, 2) expand the treated soil layers to include low-permeability regions, and 3) reduce aqueous-phase concentrations and assist in desorption of contaminants from soil particle surface.

6.4.1.4. Liquid should be extracted from the central well clusters (deep and shallow groundwater extraction wells and vapor extraction wells) at a rate equal to or greater than the rate at which groundwater is replaced by the expanding steam zone, or typically between 100 and 300% of the equivalent steam injection rate (expressed as $kg \cdot s^{-1}$ or $lb \cdot hr^{-1}$ of water). During steam zone expansion, extraction should be aggressive to create a driving force towards the central extraction well clusters. During steam cycling operations, the extraction rates may be varied to optimize the steam flow, to prevent stagnant zones, and to achieve uniform heating of the entire source zone. The vacuum pressure is typically 50.7 kPa (0.5 atm), but should be less than the minimum predicted vacuum during the shut-in portion of pressure cycles.

6.4.1.5. Vapor should be extracted through the whole period of operation using a well-head vacuum. The actual vacuum depends on the steam injection rate, the observed groundwater level in the central groundwater extraction well, and the operation of the effluent treatment system. The applied vacuum will assist in directing vapors towards the center wells, and, thus, control the heated zone.

6.4.1.6. During the entire operation period, sub-atmospheric pressure should be maintained in the shallow vadose zone, minimizing the risk of upward migration of contaminants to the soil surface. Vadose zone air pressure should be monitored, if feasible, based on the operational conditions.

6.4.1.7. The number and location of extraction and injection wells required is highly site-specific and depends on many factors, such as extent and depth of the contamination, physical and chemical properties of the contaminants, soil characteristics, and most important, soil permeability. The steam zone development can be estimated by a number of mathematical methods (see Paragraph 6.6).

6.4.1.8. Typical temperature monitoring detail is presented in Figure 6-6, while a simplified process and instrumentation diagram for a steam injection system is presented in Figure 6-7.

6.4.2. *Energy Input and Conveyance Systems*. A typical steam injection system consists of steam injection wells, groundwater/vapor extraction wells, conveyance piping, NAPL/water separator, transfer pump, controls, and gas/water treatment equipment. Figure 6-7 shows an example of process flow diagram of a typical steam injection system. The steam injection system usually uses steam generated by a mobile industrial steam boiler. Regulated steam is supplied from the boiler to the main treatment area, where steam pressure and flow rate are controlled at the wellhead.

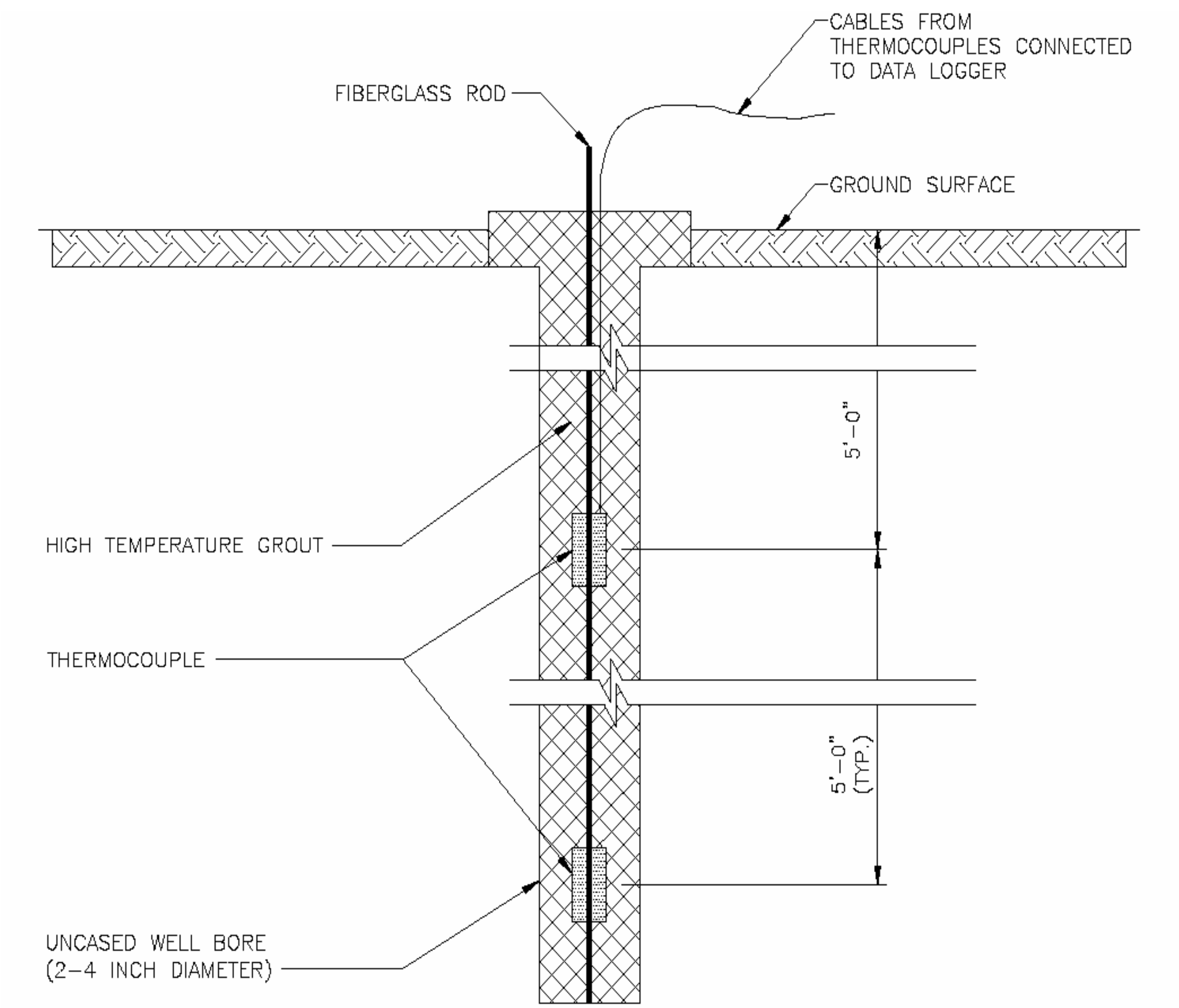


Figure 6-6. Typical Temperature Monitoring Detail.

6.4.3. Above-Ground Equipment. The treatment system usually consists of a heat exchanger, a water knockout tank, an oil/water separator, a liquid-phase effluent treatment unit, and a vapor-phase effluent treatment unit. An experienced thermal engineer should size the equipment.

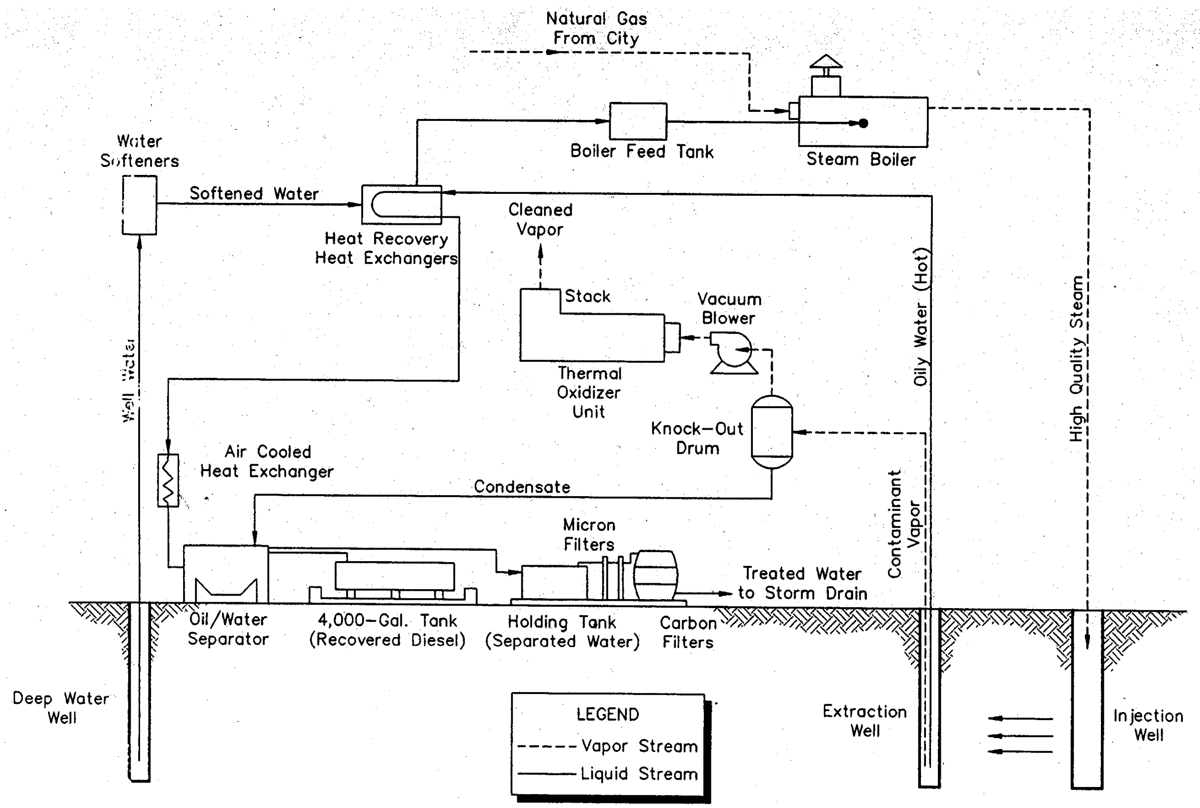


Figure 6-7. Typical Steam Injection System.

6.4.4. *Design Review Checklist*.

a. A site layout plan showing locations of steam injection wells, vapor/groundwater extraction wells, monitoring points, aboveground equipment, and buried utilities.

b. Specifications and design analysis.

c. A process flow diagram that describes the entire system, including material and energy balances, boilers, tanks, pumps, blowers, wells, conveyance piping, oil/water separators, liquid-phase treatment unit, vapor-phase treatment unit, valves, flow rates, temperatures, pressures, and composition of each “stream.”

d. A process and instrumentation diagram (P&ID) identifying equipment and components that determine the operation of the system, system controls, interlocks and automatic shutdown logic.

e. A piping drawing displaying the locations of conveyance piping and construction details.

f. A system control logic diagram that can be used to design and build a system control panel.

g. Requirements for a system enclosure and foundations for system components including storage tanks and treatment equipment.

h. An operation, maintenance and monitoring plan.

6.5. Waste Stream Treatment Options**.** This section provides a brief summary of treatment options applicable to ISTR technologies. Figure 6-8 provides a simplified process flow diagram for a treatment system used in ISTR applications to help the reader visualize the processes involved. Tables 6-1 and 6-2 summarize applications and limitations of each technology described within this section for liquid and vapor treatment, respectively. A detailed discussion of waste stream treatment design is not included, but may be found in other USACE documents (see Appendix A).

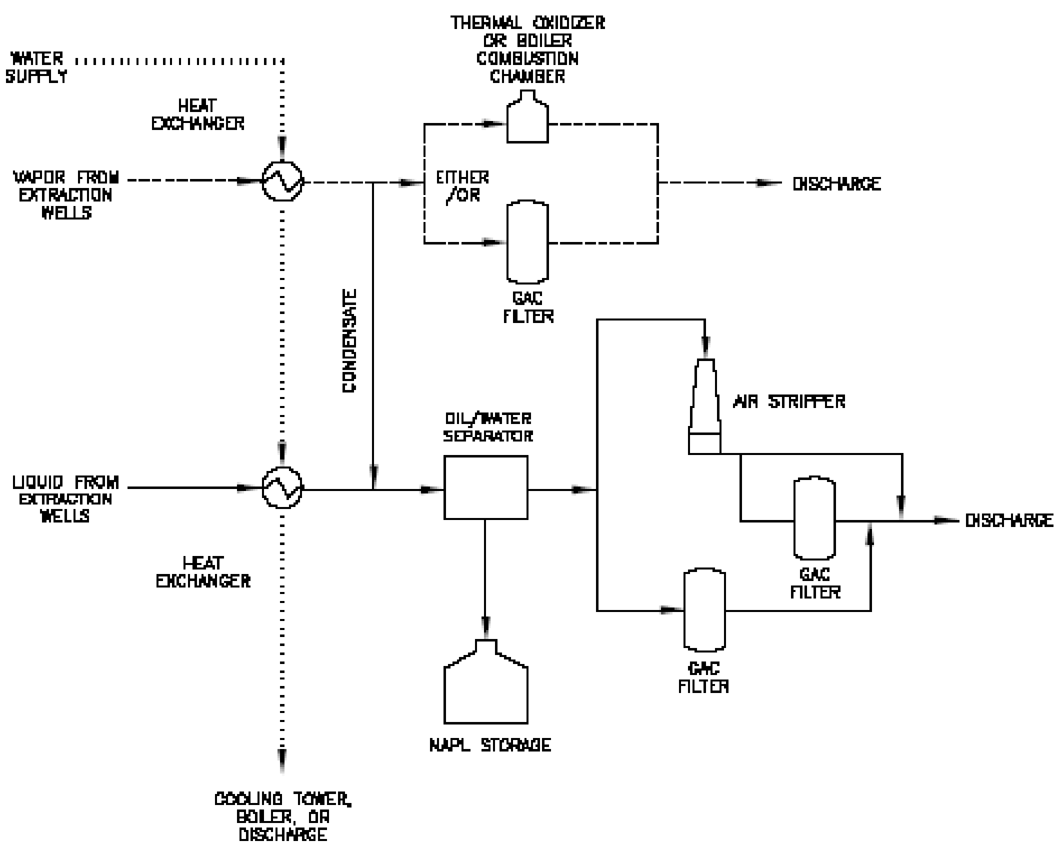


Figure 6-8. Typical ISTR Treatment Process Flow.

6.5.1. *Liquid Treatment.*

6.5.1.1. *Pre-treatment via Heat Exchange*. The temperature of the extracted liquid may affect materials of construction. For example, plastic piping may be chemically resistant, but high temperatures may cause the piping to expand and become thermally stressed. Therefore, temperature effects on the materials of construction should be considered to determine and design the most appropriate treatment method. Extracted liquid from ISTR operations must be cooled before it can be treated effectively by other methods. This is typically done by passing the liquid through a heat exchanger, in which the hot extracted liquid is cooled by air or water. Air-cooling transfers the heat directly to the atmosphere, and generally requires a large flow of air. Water for water-cooling may come from a supply source such as a well, and may be discharged, or used as boiler-feed water for steam generation. Closed systems are also used, in which cooling water is re-circulated through a cooling tower.

6.5.1.2. *Pre-treatment via Oil/Water Separators*. Oil/water separators are used to remove NAPL from the groundwater stream prior to physical, chemical, or biological treatment of dissolved constituents. Gravity separation is typically used, where separation is achieved by the difference in liquid densities.

6.5.1.3. *Pre-treatment via Dissolved Air Flotation*. Dissolved air flotation (DAF) devices may be used to remove NAPL or suspended solids in the groundwater stream by the introduction of gas bubbles, usually air. Solids and NAPL adhere to the bubbles, float to the water surface, and are removed by a skimming mechanism. Solids that settle out are conveyed out of the tank by a screw auger on the bottom of the tank.

6.5.1.4. *Pre-treatment via Carbon Adsorption*. Carbon adsorption is widely used and is applicable to a broad range of soluble organic compounds. Dissolved organic compounds adsorb onto the carbon particles. Typically, configurations are of the fixed-bed type where units are operated in parallel or series. Operation in series typically uses a secondary unit, which acts as a backup when the primary unit is out of service. Once carbon adsorption capacity is reached, carbon is either regenerated or properly disposed of. Carbon adsorption units may also be used as a polishing step for other treatment methods, prior to discharge. Other media (e.g., sorptive clays) may also be used.

6.5.1.5. *Pre-treatment via Biological Reactors*. Biological reactors have typically been used in municipal wastewater applications. However, this technology can be effectively used to treat groundwater contaminated with aerobically degradable hydrocarbons such as BTEX and other fuel components, PCP, and relatively soluble creosote components (e.g., naphthalene). Biological reactors use microorganisms to degrade organic contaminants to carbon dioxide and water. Volatile organics are also removed by volatilization as a competing mechanism. Typical reactor components include an aeration basin, clarifier, and digestion tank where wasted sludge is further concentrated. Final dewatering of waste sludge is usually accomplished with a filter press. A properly maintained biological reactor can provide significant cost savings over other treatments methods, such as carbon adsorption. However, the microorganisms can be sensitive to changes in temperature and contaminant concentrations, and may require long periods of acclimation for operational changes. Bioreactors should be used with caution; as the steam front propagates, or as the subsurface heats up, NAPL, in significant quantities, can be recovered, which can upset the treatment systems. Further, the NAPL recovery can occur rapidly, with little warning from the monitoring data that are typically employed. The microorganisms are also sensitive to changes in the dissolved oxygen concentration within the aeration basin. Rapid increases in contaminant concentrations or a malfunction in aeration system can reduce dissolved oxygen levels in the basin, and result in inadequate removal of contaminants. A functional biological reactor should be appropriately designed for the anticipated flow rates and contaminant concentrations. Owing to the potential for highly variable influent concentrations and the upset of the bioreactor, this treatment technology is not recommended for use during ISTR applications. At least one SEE site has faced difficulties with the application of bioreactors to treat creosote-related contaminants. Any use of this technology must consider mechanisms to address the variability of influent concentrations.

6.5.1.6. *Pre-treatment via Air Stripping*. Air stripping involves the mass transfer of volatile contaminants from water to air. This process is typically conducted in a packed tower. The typical packed tower air stripper includes a spray nozzle at the top of the tower to distribute contaminated liquid over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect treated liquid. Vapors generated from an air stripper may require treatment before discharge.

6.5.1.7. *Post-Treatment*. Primary treatment methods may not always be able to achieve applicable emissions standards owing to inherent inefficiencies or because of changed influent characteristics. In these situations, additional treatment methods may be used as a polishing step. For example, carbon adsorption is often used as a polishing or backup method for a biological reactor or air stripper.

6.5.1.7.1. Sand filters may be used to remove suspended solids in the groundwater stream. Solids build up and the unit is typically backwashed. Frequency of backwash depends on the solids concentration of the stream entering the filter.

Table 6-1. Groundwater Treatment Technologies.

Technology	Application	Limitations
Carbon Adsorption	• Target compounds include hydrocarbons, semi-volatile organics, and explosives, halogenated VOCs. • Effective as a polishing step to other treatment technologies. • High contaminant removal efficiencies. • Effective for removing contaminants of low concentrations from a wide range of flow rates. • Effective for removing contaminants of high concentrations from low flows (depends on size of vessel).	• Multiple contaminants may impact performance. • High-suspended solids and/or oil and grease may cause fouling and require frequent treatment. • Spent carbon must be regenerated (on or offsite) or properly disposed. • Can be costly for highly mobile compounds (low Koc). • Biological growth on carbon or high particulate loadings can reduce flow through the bed. • Elevated liquid stream temperatures may increase vessel corrosion. • Water should be cooled prior to treatment.
Aerobic Biological Reactors	• Primarily used to treat SVOCs and fuel hydrocarbons.	• Residual organic sludge that is generated must be properly disposed. • Some compounds are difficult or slow to degrade. • Cold or hot temperatures or rapid temperature fluctuations can cause operational difficulties. • Volatile organics may require air emission controls or pretreatment. • High contaminant concentrations may be toxic to microorganisms. • Difficulties in acclimating microorganisms to changing contaminant concentrations, which could result in a longer startup time.
Air Stripping	• Primarily used to treat VOCs. • May be applicable to certain halogenated SVOCs.	• Contaminants are not destroyed but physically separated from the liquid stream to air. The effluent air stream is subject to regulatory standards, and may need further treatment. • May not be fully effective at all times, and additional groundwater treatment may be necessary. • Large surges in influent concentrations can reduce removal efficiency. • Cold weather can reduce efficiency.

Technology	Application	Limitations
		• Air stripping is not as effective for compounds with low Henry's Law constants or high solubilities. • The presence of solids in the liquid stream may foul packed towers requiring more frequent cleaning. Packing material may be chemically incompatible. • High concentrations of chlorinated compounds can turn packing material brittle, resulting in annual replacement of material. • Bio-fouling and mineral deposition to be expected. • An increase in temperature may contribute to corrosion of packing and tower/tray materials.
Dissolved Air Flotation	• Total suspended solids (TSS) and NAPL levels up to 900 milligrams per liter, removal efficiency of 90 % has been recorded.	• Varying influent will affect performance technology • Sludge generated will require disposal • Air released in unit unlikely to strip volatile organics and will require controls. • Relative high liquid stream temperatures may contribute to corrosion of tanks and associated valves and fittings.

6.5.2. *Vapor Treatment*.

6.5.2.1. *Pretreatment via Heat Exchange*. Extracted vapor from ISTR operations must be cooled before it can be treated effectively by other methods. This is typically done using air or water as the coolant through a heat exchanger/condenser. Air-cooling transfers the heat directly to the atmosphere, and generally requires a large flow of air. Water for water-cooling may come from a supply source such as a well, and may be discharged, or used as boiler-feed water for steam generation. Closed systems are also used, in which cooling water is re-circulated through a cooling tower. Condensed vapor is then conveyed to the liquid treatment system. If very high levels of contaminants are present in the condensate, a pre-treatment step may be required before the condensate can be introduced into the liquid treatment system.

Table 6-2. Vapor Treatment Technologies.

Technology	Application	Limitations
Carbon Adsorption	• Target compounds include hydrocarbons, semi-volatile organics, explosives, and halogenated VOCs. However, removal of high contaminant concentrations using vapor-phase carbon may not be economically favorable. Pretreatment of the VOC stream, followed by the use of a vapor-phase GAC system as a polishing step would be more cost-effective.	• Spent carbon transport may require hazardous waste handling. • Spent carbon must be disposed of or regenerated (off or on site) and the adsorbed contaminants must be destroyed, or regenerated on or offsite. • Relative humidity greater than 50% can reduce carbon capacity. • Elevated temperatures from ISTR operations (greater than 38° C or 100° F) inhibit adsorption capacity. • Biological growth on carbon or high particulate loadings can reduce flow through the bed.
Thermal/Catalytic Oxidation	• The target contaminant groups for oxidation are nonhalogenated VOCs and SVOCs, and fuel hydrocarbons.	• If sulfur or halogenated compounds or high particulate loadings are in the emissions stream, the catalyst can be poisoned/deactivated and require replacement. • Destruction of halogenated compounds requires special materials, construction, or special catalysts (if using a catalytic oxidizer). • Influent gas concentrations must be < 25% of the lower explosive limit for catalytic and thermal oxidation. • The presence of chlorinated hydrocarbons (see comment above) and some heavy metals (e.g., lead) may poison a particular catalyst.
Energy Recovery	• Primarily applicable for fuel hydrocarbons and some SVOCs.	• Some contaminants can damage combustion chambers or burners. • Some combustion chamber configurations cannot achieve emissions standards for certain contaminants. • Fine-tuning of the system may be required to meet emissions standards.

6.5.2.2. *Pretreatment via Drying/Dehumidification*. Primary vapor treatment methods may require the vapor stream to have a low relative humidity for optimal operation. A knockout tank or a mechanical dryer may be used to lower the relative humidity of the vapor prior to primary treatment.

6.5.2.3. *Treatment via Carbon Adsorption*. Vapor phase carbon adsorption is similar to the liquid treatment application, where compounds adsorb from the vapor stream onto the carbon particles. Operational configuration may be either in parallel or in series. Carbon can be regenerated or disposed of off-site. High relative humidity or temperature in the vapor stream decreases the efficiency of the treatment.

6.5.2.4. *Treatment via Thermal/Catalytic Oxidation*. Oxidation units are used to destroy contaminants in the vapor stream. Thermal oxidation units are typically single chamber and refractory-lined, equipped with a propane or natural gas-fired burner, and a stack. Burner capacities in the combustion chamber range from 527,000 to 2,100,000 $kJ \bullet hr^{-1}$ (0.5 to 2 million Btu) per hour. Operating temperatures range from 760 to 927°C (1400 to 1700°F), and gas residence times are typically 1 second or less. Catalytic oxidation units use a catalyst to accelerate the rate of oxidation, which enables the unit to destroy contaminants at a lower temperature than conventional thermal oxidation units. VOCs are thermally destroyed at temperatures typically ranging from 320 to 540°C (600 to 1000°F). Thermal oxidizers can often be converted to catalytic units after initially high influent contaminant concentrations decrease to less than between 1000 and 5000 ppmv. This method may not be appropriate for treatment of halogenated compounds, owing to the formation of hydrochloric acid, which could foul the catalyst.

6.5.2.5. *Treatment via Energy Recovery*. Energy recovery (i.e., using the extracted vapor as a fuel) is a vapor treatment alternative to common technologies. Energy recovery is used for in situ thermal techniques involving steam injection, where the extracted vapor can be introduced to the fuel stream for a gas or oil-fired boiler. Using extracted contaminant vapors as an energy source for the boiler will likely require additional monitoring of the stack gases to assure compliance with air discharge permit or other requirements.

6.5.3. *Process Residuals and Offsite Waste Management*. Process residuals generated from the treatment process will need to be managed. Process residuals include spent carbon, filter material, and sludges. Such residuals should be characterized for proper disposal. Disposal options depend on cost. The spent granulated carbon may be taken off-site for disposal (landfill or incineration) or regeneration. Depending on the amount of carbon usage, regeneration on-site may be more cost-effective. NAPL separated in the DAF or other oil-water separator must be stored for proper disposal.

6.6. <u>Other System Considerations</u>.

6.6.1. *Enclosures/Buildings*. ISTR methods may be housed inside buildings or exposed to the elements. Systems inside buildings should have adequate ventilation to prevent buildup of vapors. Mechanical and electrical components placed outside should be rated as weather proof.

6.6.2. *Surface Covers*. To control vapor migration, a surface cover or impermeable cap should be constructed at the site. Soil pore spaces can be filled by water infiltrated from the surface, which reduces the airflow. If horizontal extraction wells are installed, infiltration water can fill the trenches. Installation of a surface cover helps minimize infiltration water. In addition, the radius of influence of the vapor recovery wells may be increased using an impermeable cap at the surface. Short-circuiting of the surface air will be prevented if a good surface seal is achieved and forces air to be drawn from a greater distance.

6.6.2.1. Concrete or asphalt is the most common surface cover. If the site has pre-existing pavement, it may act as the surface cover. The pavement should be sealed so that it is water-resistant and relatively impervious to airflow.

6.6.2.2. A temperature-and contaminant-tolerant geomembrane may be used for the ISTR surface cover if no pavement exists at the site. The area should be graded and smoothed to eliminate ponding of rainwater. Follow the installation procedure of the geomembrane provided by the manufacturers.

6.6.2.3. To minimize damage to the geomembrane by personnel, equipment, or the natural elements, an appropriate (15–30 cm) thickness of fill (pulverized soil, sand, or pea gravel) may be placed over it. It is recommended that the geomembrane not be left exposed. However, if exposure is not avoidable, its perimeter should be keyed into a trench and backfilled to prevent short-circuiting of air. In addition, run-off water should be directed to ditches that divert the water away from the treatment area. Surface covers are discussed in detail in EM 1110-1-4001, Paragraph 5.15.

6.6.3. *Noise Control*. Sound levels are measured in decibels (dB) using a logarithmic scale. The standard measure for environmental sound levels is the A-weighted sound pressure level (dBA). The A-weighting scale was developed to simulate the frequency response of the human ear to sounds at typical environmental levels.

6.6.3.1. The U.S. EPA has identified yearly day-night average sound levels, Ldn, sufficient to protect public health and welfare from the effects of environmental noise. The U.S. EPA emphasizes that since the protective sound levels were derived without concern for technical or economic feasibility, and contain a margin of safety to ensure their protective value, they must not be viewed as standards, criteria, regulations, or goals. The U.S. EPA has no authority to regulate ambient noise levels. The Ldn should be viewed as the level below which there is no reason to suspect that the general population will be at risk from the effects of noise. According to the U.S. EPA, levels are sufficient to protect public health and welfare if they do not exceed a yearly average Ldn of 55 dBA outdoors and 45 dBA indoors in sensitive area such as residences, schools, and hospitals (USEPA 1977).

6.6.3.2. OSHA has established maximum permissible worker noise exposure levels to protect against hearing damage. The level is based on a worker's noise exposure over a specific time period. For example, as stipulated in Title 29 of the Code of Federal Regulations, Part 1910, a worker cannot be exposed to an average sound level in excess of 90 dBA for over an 8-hour period. When noise exposure exceeds the permissible level, noise must be reduced through feasible engineering or administrative controls. When such controls fail to reduce the noise exposure to a permissible level, personal protective equipment must be provided and used to reduce the noise exposure. In addition, when worker noise exposure exceeds 85 dBA over an 8-hour period, the employer must provide hearing protection and establish an annual audiometric testing program to track potential hearing loss. Therefore, OSHA requirements allow areas within facilities to exceed 85 dBA, provided that feasible noise control has been implemented and these areas are designated as high noise areas requiring hearing protection at all times. Compliance with the OSHA noise exposure limits will be achieved by providing equipment noise mitigation and by identifying the high noise areas with warning signs that prescribe hearing protection.

6.6.3.3. The construction phases of the ISTR system consist of site preparation, injection/extraction/heater well or electrode drilling, equipment erection, and startup. Noise emissions vary with each phase of construction, depending on the activity and the associated equipment. Construction activities should be scheduled during daytime periods (0700 to 2000) to the extent possible. Some activities may require extended hours of operation because of scheduling constraints. Nighttime construction should be limited to low-noise-producing activities to the extent possible.

6.6.3.4. The primary noise sources anticipated from the treatment site are the steam generator, the air compressor, the heat exchanger, blowers for vapor recovery and air strippers, and the thermal oxidizer exhaust stack. Noise reduction design features should be included where feasible (e.g., stack silencer for the thermal oxidizer stack, low-noise fans on the heat exchanger, enclosure of the air compressor, blowers, etc.).

6.6.4. *Subsurface Barriers*. NAPL migration may be contained, and groundwater recharge may be controlled with the use of subsurface barriers. The type of barrier wall should be selected based on the specific installation configuration, required installation depth, contaminant type, and installation cost. Typical subsurface barriers are, but not limited to soil-bentonite (S-B) slurry, (steel or plastic) sheet piles, pressure-injected grout curtains, or a synthetic material (e.g., HDPE).

6.6.4.1. Slurry wall barriers are constructed by excavating a relatively narrow vertical trench, typically 0.6 to 1.5 m (2 to 5 feet) wide, through a previous soil stratum to an underlying impervious layer. The trench is filled with bentonite-water slurry during excavation to stabilize the trench walls, allowing excavation to continue through the slurry, to the desired depth. Once the desired depth has been reached, the slurry trench is backfilled with a soil/bentonite/water mixture designed to provide a low-permeability barrier wall (10^{-7} to 10^{-8} cm•s^{-1}). Designers should consult guide specification CEGS 02444, Soil-Bentonite Slurry Trench for HTRW Projects, and other USACE reference documents if considering use of an S-B cut-off wall. Subsurface barriers are discussed in more detail in EM 1110-1-4010, Chapter 5-10.

6.7. Modeling.

6.7.1. *General*. Mathematical models have proven to be useful for simulating and predicting physical and chemical processes during thermal treatment. Modeling efforts may utilize a variety of mathematical tools, ranging from simple engineering calculations to sophisticated numerical modeling codes. The level of detail required for thermal modeling depends on a number of factors, including site conditions, cleanup objectives, and budgetary constraints. Always remember that the utility of modeling results depends on the quality of the input data. In general, appropriately selected and properly implemented modeling procedures should result in construction and operations cost savings that are much greater than the cost of the modeling. Previous guidance on modeling for soil vapor extraction systems (USEPA 1995) is also applicable to ISTR projects.

6.7.1.1. Note that ISTR simulations can yield misleading results unless they are very carefully performed. Input parameters such as the anisotropy ratio (horizontal to vertical permeability) and low-permeability lenses can totally control the heating pattern, and should be captured in the models. Models that are intended for uses other than preliminary design analyses should incorporate the following features:

a. Geological layering and heterogeneity.

b. Intrinsic permeability (affects injection rates and radius of influence).

c. Anisotropy ratio of major layers (influences the degree of vertical steam rise, and the ability to heat the base of thick aquifers).

d. Heterogeneity and discontinuities in low-permeability layers (affects upward steam migration through aquitards).

Ideally, predictive modeling should be done using a model that has been calibrated or verified by comparison to actual field steam or heat flow (Ochs et al. 2003).

6.7.2. *Applicability and Objectives*. Modeling is primarily applicable to feasibility studies and design analyses of thermal remediation projects; however, models may also be used during operations and long-term monitoring. The objectives of modeling should be carefully weighed before selecting the modeling strategy. Minimum objectives for modeling would include estimation of the following parameters:

a. Injection and recharge rates for wells — These data are necessary for designing fluid conveyance and treatment systems.

b. Well or electrode spacing and design — Trials with different well spacings, depths, and screen lengths can help optimize design for energy or steam distribution, and contaminant recovery.

c. Heating duration — Simulations can predict the length of time required to achieve treatment temperature throughout the target treatment zone for a given well spacing and energy input.

d. Energy requirements — Electrical power or steam injection requirements must be predicted to estimate plant capacities, total energy costs, and project duration.

6.7.2.1 Additional objectives could include evaluations of the following:

a. Contaminant removal—Models can be used to evaluate the effectiveness of the removal of dissolved, sorbed, or NAPL contaminants, and to predict the removal rate, including the effects of chemical reactions such as hydrolysis, oxidation, and pyrolysis.

b. Site hydraulic control—To prevent spreading of contaminants, it may be necessary to control groundwater flows during treatment.

c. Aquitard heating—Predictions of time and energy required to heat low-permeability materials may be useful for system design or selection of the treatment strategy.

d. Heat losses—Evaluations of the extent of heat losses to surrounding zones and to the atmosphere, and the need for surface insulation; identification of zones where contaminants may be deposited due to condensation; assessments of the effects of heating on sensitive utility lines and structures, and the need for protective measures such as insulation jacketing.

e. Environmental impacts—Thermal effects to biota surrounding the treatment area, or on the ground surface above the treatment zones may be of concern.

f. Emissions—Vapor discharges and concentrations at the ground surface may be estimated.

g. Operations scenarios (including shutdown of power for sampling events).

h. Procedures such as pressure cycling, or variations of energy input, pumping, or vacuum extraction rates may be evaluated before implementing in the field.

6.7.3. *Model Solutions and Codes*. Models may be divided into two broad categories: analytical solutions or numerical modeling codes. Available solutions and codes are listed in Tables 6-3 and 6-4, along with the processes that can be modeled.

6.7.3.1. *Analytical Solutions*. Analytical solutions are relatively easy and inexpensive to use, however the results are subject to uncertainties caused by their inherent assumptions (i.e., homogeneous and isotropic media, domains of infinite horizontal extent, steady-state conditions). The following analytical solutions are applicable to thermal remediation projects.

6.7.3.2. *Energy budget calculations*. Simple thermodynamic calculations can be made of the total energy or heat input requirement to raise a given volume of soil and groundwater to a required temperature (an example calculation is shown in Paragraph 6.2).

6.7.3.3. *Heat flow*. A variety of heat-transfer equations are available for estimating the migration of heat through materials by both conduction and convection (Carslaw and Jaeger 1959, Incropera and DeWitt 1996).

6.7.3.4. *Liquid Flow*. Well-hydraulics equations are applicable to all in situ thermal technologies that employ liquid extraction wells. Radial flow solutions such as the Thiem (1906), Theis (1935), or Jacob (1940) equations may be used to estimate groundwater pumping rates. If single-phase conditions can be assumed, and if adjustments are made for liquid density and viscosity, the same equations can also be used to estimate NAPL removal rates for known NAPL thicknesses.

6.7.3.5. *Vapor flow*. Well-hydraulics equations that have been adapted for gas flow (USACE 2002) are applicable to all in situ thermal technologies that employ gas extraction wells and may be used to estimate gas extraction rates. The same equations may also be used to estimate steam or air injection rates. Steady-state solutions are applicable to gas extraction and injection, because underground vapor flow tends to stabilize rapidly. If pressure differentials greater than 0.2 atm exist within the treatment zone, however, the equations must also be adapted for compressible fluid flow (Massman 1995). Additional gas-flow equations for planar sinks (USACE 2002) may be used to estimate non-condensable gas leakage through barrier walls, from the ground surface, or through low-permeability caps.

6.7.4. *Numerical Modeling Codes*. Numerical models tend to be more costly and labor-intensive than analytical solutions, but they can simulate site geometry and stratigraphy, heterogeneous and anisotropic media, multiple processes, interactions between multiple flow and energy sources, and time-variable conditions or treatment operations. A distinct advantage of numerical models is the ability to predict the 3-dimensional shape and migration pattern of steam zones and NAPL-condensation zones; this capability has proven useful for well design and selecting well/electrode spacing. In general, numerical simulations are appropriate for projects with relatively complex site conditions or stringent cleanup objectives. Three broad classes of modeling codes are listed below, in order of increasing data requirements.

6.7.4.1. *Groundwater Models* (Single Phase, Isothermal). If control of contaminant migration is necessary, conventional groundwater models may be used to simulate groundwater flow patterns during thermal treatment. This is particularly convenient for projects where a site groundwater model has already been developed.

6.7.4.2. *Combined Heat, Groundwater and Gas Flow with Phase Changes (2-Phase, Thermal)*. This is the most useful type of model for simulations of steam and heat migration. Most of the required fluid property data are already contained in the computer code, and typical design issues involving wells, soil caps, subsurface barriers, and operations scenarios can be addressed.

Table 6-3. Applicability of Models to Individual Technologies.

Analytical Solution or Numerical Modeling Code	Technology: Thermal Conduction	Technology: Electrical Resistance Heating	Technology: Steam Injection	Reference
ANALYTICAL SOLUTIONS				
Fluid Flow				
Radial liquid flow to a well	X	X	X	Jacob, C. E. (1940); Theis, C. V. (1935), Thiem (1906)
Radial gas flow to/from a well	X	X	X	USACE (1995); USEPA (1998)
Linear gas flow to a plane sink	X	X	X	USACE (1995)
Heat flow				
Heat balance	X	X	X	
Radial flow from a line source	X			Carslaw and Jaeger (1959)
Linear flow from a plane source	X			Carslaw and Jaeger (1959), Incropera and DeWitt (1996)
Combined heat and fluid flow				
Marx-Langenheim equation			X	Marx and Langenheim (1959)
Marx-Langenheim with radial gas flow			X	USEPA (1999)
Van Lookeren solution			X	Van Lookeren (1983)
NUMERICAL MODELING CODES				
(All computer codes run on Pentium-compatible PCs, and can simulate flow of heat, water vapor, and liquid water, with phase changes.)				
HYDROTHERM	X	*	X	U. S. Geological Survey Hydrologic Analysis Software Support Program 437 National Center Reston VA 20192
M2NOTS	X	*	X	Kent Udell 6147 Etcheverry Hall University of California Berkeley CA 94720-1740
NUFT	X	X	X	John Nitao Lawrence Livermore National Laboratory 7000 East Ave. Livermore, CA 94550-9234
PORFLOW	X	*	X	Analytical and Computational Research, Inc. 1931 Stradella Road Bel Air, CA 90077
STAR	X	*	X	Science Applications International Corp. 10260 Campus Point Drive San Diego, CA 92121
STARS	X	X	X	Computer Modeling Group Paragon Center One 450 Gears Road, Suite 860 Houston, TX 77067
STOMP	X	X	X	Mark White Pacific Northwest National Laboratory 3200 Q Avenue Richland WA 99352
TETRAD	X	X	X	ADA International Consulting 705 Hawkwood Blvd. NW Calgary, Alberta T3G 2V7 Canada
TOUGH2 (Version 2)	X	*	X	Karsten Pruess Lawrence Berkeley National Laboratory 1 Cyclotron Road, 90-1116 Berkeley, CA 94720

Table 6-4. Features of Numerical Modeling Codes. Minimum capabilities include simulation of liquid water, water vapor, and heat flow with water phase changes. In general, codes with pre-processors and post-processors are easier to use.

Code	Features									
	NAPL Flow	Interphase partitioning	Solute transport	Vapor transport	Emulsions	Chemical reactions	Electrical fields	Graphical user interface	Pre-processor	Post-processor
HYDROTHERM										X
M2NOTS	X	X	X	X						
NUFT	X	X	X	X		[1]	X	[2]	[2]	[2]
PORFLOW	X		X			X		X	X	X
STAR		X	X	X		[1]		[3]	[3]	[3]
STARS	X	X	X	X	X	X	X	X	X	X
STOMP	X	X	X	X		[1]	X			
TETRAD	X	X	X	X		X	X	[3]	[3]	[3]
TOUGH2 (v.2)	X	X	X	X		[1]		[3]	[3]	[3]

[1] Decay only.
[2] GMS-NUFT only.
[3] Commercially available.

6.7.4.3. *Combined Heat, Groundwater, Gas, and NAPL Flow with Phase Changes (3-Phase, Thermal)*. Many multiphase-thermal modeling codes can simulate NAPL flow as well as mass transfer between NAPL, aqueous and gas phase. Some of the codes can simulate separate contaminant compounds in the NAPL, or “pseudocomponents” with averaged properties for combined groups of contaminants. The effectiveness of the thermal treatment can be evaluated, and design parameters such as NAPL recovery rates, contaminant concentrations in recovered fluids, and cleanup times can be estimated. A few numerical codes can also simulate chemical reactions involving contaminant constituents.

6.7.5. *Input Data*. Media or formation data required for modeling include soil physical properties (density, porosity), thermal properties (heat capacity and conductivity), and hydraulic properties (permeability, pressure-saturation-permeability characteristics). Groundwater and steam properties, such as density, viscosity, and thermal characteristics, are temperature-dependent; this information may be obtained from steam tables, and is generally computed automatically by the numerical modeling codes. If groundwater and soil contamination are simulated, chemical transport properties for each component are required (solid-liquid and liquid-vapor partitioning coefficients, enthalpy, and degradation constants). NAPL flow simulations require additional NAPL properties, including density, viscosity, and pressure-saturation-permeability characteristics. Since NAPL physical and chemical properties are temperature-dependent, care needs to be taken to utilize appropriate data for the required temperature ranges.

6.7.6. *Implementation of Model Results*. Models may be used at various stages of project development. A model may be useful in the feasibility stage to evaluate potential energy costs or environmental effects for one or several technologies. Models are particularly important during the design stage, when plant and well-field parameters must be developed. The trade-off relationship between cost, performance, and project duration can also be evaluated by modeling. Sensitivity studies, based on known uncertainties in site soil and fluid properties, can be used to develop safety factors for equipment design. Models, providing useful information for planning treatment cycles, treatment zone size, monitoring programs, or project duration, may also simulate operation strategies. Models that are updated and calibrated during testing and operations may be used to evaluate operational problems, and to provide refined designs based on initial or pilot test results. Predictions of cooling rates, contaminant degradation rates, and required duration for long-term monitoring can by made through the continued use of a project model, after completion of active thermal treatment.

The applicability of various solutions or modeling codes to specific technologies is discussed in this paragraph. See Table 6-3 for references and availability.

6.7.7. *Modeling Aspects for Thermal Conductive Heating*.

6.7.7.1. *Analytical Solutions*.

6.7.7.1.1. *Energy Budget*. The energy input requirement for a known treatment volume can be calculated (example shown in Paragraph 6.2.), based on the required treatment temperature, thermal capacities of the soil and groundwater, and the latent heat required to convert the groundwater to steam, as necessary. Additional allowances may be needed for heat lost to the atmosphere or surrounding soil.

6.7.7.1.2. *Heat Conduction Equations*. Heat flow from heater blankets and heater wells can be simulated with transient solutions for linear heat conduction from a plane source, and radial conduction from a line source, respectively. A summary of analytical equations used to describe phenomena in thermal conduction processes is available (Stegemeier and Vinegar 2001).

6.7.7.1.3. *Superposition*. Temperatures within an area being treated with multiple heating wells and blankets can be calculated by superimposing planar and line sources (i.e., summing the predicted temperature change at a given point attributable to each source, to predict the total temperature change at the point due to all sources).

6.7.7.1.4. *Gas Flow Equations*. As discussed, compressible fluid flow equations may be used to estimate gas extraction rates for contaminant recovery.

6.7.7.2. *Numerical Modeling Codes*. All of the numerical modeling codes listed in Tables 6-3 and 6-4 may be used for simulating conduction heat sources. The sources may be implemented as boundary conditions - for example, the upper model boundary for a heater blanket, or a column of cells for a heater well. Some of the codes have well options that include energy input only with no fluid. Sources may be given a specified temperature, or a specified thermal energy input rate.

6.7.8. *Modeling Aspects for Electrical Resistivity Heating*.

6.7.8.1. *Analytical Solutions*. The energy budget calculation described in Paragraph 6.7.7.1. is also applicable to electrical resistivity heating; however the total energy requirement must be converted to electrical energy units (i.e., joules or Btu converted to kilowatt-hours). In current practice, electrode spacings are determined by the ratio of the diameter of the electrode array to the diameter of the electrode* (D:d), modified by engineering judgment or "rules of thumb" based on past experience, rather than with analytical solutions.

6.7.8.2. *Numerical Modeling Codes*. All of the numerical codes listed in Tables 6-3 and 6-4 may be used for simulating electrical resistivity heating sources, by using the simplifying assumption that the input electrical energy is applied uniformly within a finite soil volume surrounding or between electrodes. Some of the computer codes can also simulate the electrical field as well as soil heating based on electrical currents and soil resistance. An essential feature in electrical heating codes is the ability to vary soil resistance with temperature and fluid saturation; this capability is particularly important near electrodes, where the flow of electrical current can be impeded by dry soil conditions.

6.7.9. *Modeling Aspects for Steam Injection*.

6.7.9.1. *Analytical Solutions*.

6.7.9.1.1. *Radial Gas Flow*. As discussed, steady-state radial compressible-fluid flow equations may be used to estimate both steam injection and gas extraction rates.

6.7.9.1.2. *Steam-Zone Radius*. The Marx-Langenheim equation (Marx and Langenheim 1959) is widely used for calculating the growth of a cylindrical steam zone around a single steam injection well, for an assumed injection rate and steam temperature. The optimum well spacing can be selected as the predicted steam-zone radius at a desired steam-breakthrough time (time for steam to reach the extraction wells), typically in the range of 2 to 3 weeks. Users of the Marx-Langenheim equation need to consider the potential for underestimation of the steam radius when the actual steam volume will be non-cylindrical, owing to the effects of steam-override and adjacent injection wells.

6.7.9.1.3. *Coupled Gas Flow and Steam-Radius Calculations*. A steady-state gas flow equation may be combined with the Marx-Langenheim equation to simulate a variable steam injection rate with time, as the steam radius increases. The calculation is implemented in a spreadsheet, over a series of time steps (Lawrence Livermore National Laboratory 1994).

6.7.9.2. *Numerical Modeling Codes*. All of the numerical modeling codes listed in Tables 6-1 and 6-2 are capable of simulating steam injection remediation. Most of the codes have well options that include productivity coefficients, well-efficiency corrections, and pressure control versus flow control. An important feature provided by some the modeling codes is the ability to simulate a multiphase well (i.e., pressure-controlled vapor extraction and flow-controlled liquid extraction from the same well).

6.7.9.2.1. It should be noted that steam simulations can yield misleading results unless they are very carefully done. Input parameters such as the anisotropy ratio (horizontal to vertical

* The diameter of the electrode consists of the diameter of the pipe used to construct the electrode plus the added graphite and/or steel shot.

permeability) and low-permeability lenses can totally control the heating pattern, and should be captured in the models. Models that are intended for uses other than preliminary design analyses should incorporate the following features:

a. Geologic layering and heterogeneity.

b. Intrinsic permeability (affects injection rates and radius of influence).

c. Anisotropy ratio of major layers (influences the degree of vertical steam rise, and the ability to heat the base of thick aquifers).

d. Heterogeneity and discontinuities in low-permeability layers (affects upward steam migration through aquitards).

Ideally, a predictive model that has been calibrated or verified by comparison to actual field steam flow should be used (Ochs et al. 2003).

6.7.10. *Checklist for Review of Models for In Situ Thermal Remediation*. A checklist for review of models for ISTR is located in Appendix C of this document. This list is focused on issues specific to thermal and multiphase modeling. General guidelines for the use of groundwater models are also applicable (Anderson and Woessner 1992, American Society for Testing and Materials 1996, 1997b).